

PINWHEEL NEBULA AROUND WR 98A

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Draft version February 1, 2008

ABSTRACT

We present the first near-infrared images of dusty Wolf-Rayet star WR 98a. Aperture masking interferometry has been utilized to recover images at the diffraction-limit of the Keck-I telescope, $\lesssim 50$ mas at $2.2\mu\text{m}$. Multi-epoch observations spanning about one year have resolved the dust shell into a “pinwheel” nebula, the second example of a new class of dust shell first discovered around WR 104 (Tuthill, Monnier, & Danchi 1999a). Interpreting the collimated dust outflow in terms of an interacting winds model, the binary orbital parameters and apparent wind speed are derived: a period of 565 ± 50 days, a viewing angle of $35^\circ \pm 6^\circ$ from the pole, and a wind speed of $99 \pm 23 \text{ mas yr}^{-1}$. This period is consistent with a possible ~ 588 day periodicity in the infrared light curve (Williams *et al.* 1995), linking the photometric variation to the binary orbit. Important implications for binary stellar evolution are discussed by identifying WR 104 and WR 98a as members of a class of massive, short-period binaries whose orbits were circularized during a previous red supergiant phase. The current component separation in each system is similar to the diameter of a red supergiant, indicating that the supergiant phase was likely terminated by Roche-lobe overflow, leading to the present Wolf-Rayet stage.

Subject headings: stars: Wolf-Rayet, stars: circumstellar matter, stars: mass-loss, stars: variable, stars: binaries, techniques: interferometric

1. INTRODUCTION

A small fraction of Wolf-Rayet (WR) stars are known to be strong infrared (IR) sources, surrounded by shells of warm dust maintained by massive stellar winds. These systems have been classified as either “variable” or “persistent” dust-producers, based on the variability of IR flux (Williams & van der Hucht 1992). Radio observations of some “variable” WR stars have detected non-thermal emission, interpreted as the interface between colliding winds in *long-period* WR binary systems (e.g., White & Becker 1995; Veen *et al.* 1998; Williams 1998). The episodic formation of dust in these systems appears to coincide with periastron passage, the colliding winds at close binary separation (a few AU) apparently catalyzing dust formation. The radio and IR properties of the prototypical system WR 140 and other episodic dust producers have been successfully explained in the context of such wind-wind models (e.g., Moffat *et al.* 1987; Williams *et al.* 1990).

Most of the brightest infrared WRs, however, are classified as “persistent” dust producers, and these objects have been more difficult to explain. The lack of IR variability suggests that dust is being produced constantly, despite the unfavorable dust formation conditions around single WR stars (Cherchneff & Tielens 1995). This has led to the suggestion that *short-period* binaries lie buried in these optically-obscured systems with wind-wind collisions catalyzing the dust formation (see Usov 1991; Williams & van der Hucht 1992). However, other workers have argued that enough dust can form in the spherically-symmetric wind of a singular WR via novel dust formation processes (e.g., Zubko 1998). Until recently, few direct observations were

available to settle this controversy.

A diffraction-limited, multi-epoch study of these IR-bright sources at near-IR wavelengths is underway using the Keck-I telescope. Initial results for the IR-bright WR 104 (WC9 [Torres, Conti & Massey 1986]) have been published in Tuthill *et al.* (1999a), marking the discovery of the first “pinwheel” nebula. We now present the second such nebula WR 98a, firmly establishing this new class of dust shell. Although one of the IR-brightest WR stars known, WR 98a (WC8-9 [Williams *et al.* 1995]) was only recently identified through the use of IRAS data (Cohen *et al.* 1991), and no previous imaging of its dust shell has been reported. While no variability has been detected for WR 104, ~ 0.5 mag (K-band) variability has been observed for WR 98a (Williams *et al.* 1995). For this reason, it is often included as a “variable” dust producer, although this level of variability is significantly less than that observed for WR 140 and other long-period binary systems.

2. OBSERVATIONS

Aperture masking interferometry was performed by placing aluminum masks in front of the Keck-I infrared secondary mirror. This technique converts the primary mirror into a VLA-style interferometric array, allowing the Fourier amplitudes and closure phases for a range of baselines to be recovered with minimal “redundancy” noise (e.g., Baldwin *et al.* 1986). The Maximum Entropy Method (MEM) (Gull & Skilling 1984; Sivia 1987) has been used to reconstruct diffraction-limited images from the interferometric data. In order to check the reliability of the reconstructions, the MEM results have been compared with those from the CLEAN reconstruction algorithm (Högbom 1974). Further engineering and per-

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formance details may be found in Monnier *et al.* (1999), Tuthill *et al.* (1999b), and Monnier (1999).

WR 98a was observed in June and September of 1998 and April 1999 at Keck-I using the Near Infrared-Camera (Matthews & Soifer 1994; Matthews *et al.* 1996) and an annulus aperture mask. Spectral filter characteristics and the number of speckle frames (integration time 0.137 s) obtained for each observation can be found in Table 1. The unresolved star HD 163428 (spectral type K5II) was used to calibrate the atmosphere plus telescope transfer function.

Multi-epoch images of WR 98a appear in Figure 2; the high spatial resolution of the Keck ($\lesssim 50$ mas) was adequate to resolve much of the dust shell around this source. As for WR 104, the dust emission was observed to be distributed in a rotating “pinwheel” nebula, naturally explained by wind interactions between the WR and an OB-type companion in a *short-period* binary system. By inspection, the observed rotational period is 1-2 yr, corresponding to an orbital major axis of a few AU for a massive binary system. This separation amounts to only a few milli-arcseconds on the sky, unresolvable by this experiment.

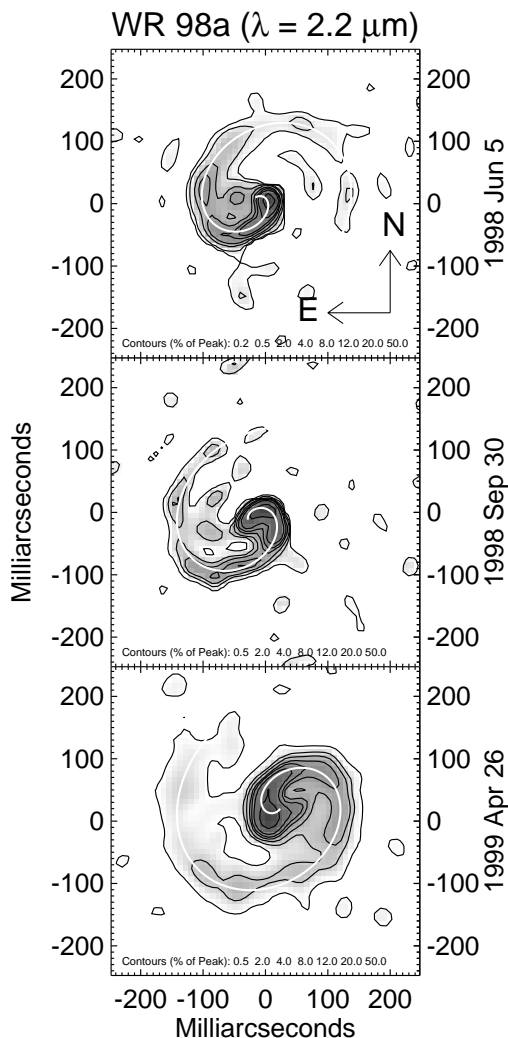


Fig 1.— Three epochs of the $2.2\mu\text{m}$ emission from WR 98a clearly show a spiral morphology. The solid line represents the best fit plume morphology based on a simple model (see §3 & 4).

Table 1. — Observing log for WR 98a at Keck-I

Date (U.T.)	λ_0 (μm)	$\Delta\lambda$ (μm)	Number of Frames
1998 Jun 05	2.269	0.155	200
1998 Sep 30	2.2135	0.427	100
1999 Apr 26	2.269	0.155	200
	2.2135	0.427	100

3. THE EMISSION MODEL

In the case of a WR+OB binary, both stars drive their own wind, but the momentum in the WR wind is expected to be significantly higher than for the companion wind (e.g., by a factor of ~ 60 for WR 146 [Dougherty *et al.* 1996]). Hence, a shock will form between the stars much closer to the OB companion, and the colliding gas will be compressed and ultimately flow out of the interface region in a wake behind the OB-star. Although the detailed mechanisms are not known, dust formation is catalyzed in such systems (Moffat *et al.* 1987; Williams *et al.* 1990; Williams & van der Hucht 1992). Generally, it is thought that dust can form in the compressed wake when the gas cools sufficiently. High gas density may not be the only important condition, as recent work indicates that the presence of hydrogen from the OB companion wind may play an important dynamical role in efficient dust formation (Le Teuff 1999).

Regardless of the dust formation mechanism, the highly collimated appearance of the spirals in the WR 104 and WR 98a suggest that wind momenta ratios $(\dot{M}v_\infty)_{\text{WC}}/(\dot{M}v_\infty)_{\text{O}}$ in these stars are indeed quite high, perhaps $\gtrsim 100$ (Canto, Raga & Wilkin 1996). A more quantitative discussion concerning the flow of cold gas from the wind-wind collision region can be found in Usov (1991).

As was done for WR 104 (Tuthill *et al.* 1999a), the multi-epoch morphology of the WR 98a spiral can be used to extract parameters of the obscured binary system, including the period, inclination, and wind speed. Our model assumes that the dust forms in the wind moving at constant (terminal) velocity. In this case, the dust in the spiral is not flowing *along* the spiral shape, but rather the dust is flowing purely radially away from the binary; the spiral only appears to rotate in time due to the rotating dust formation site associated with the OB-companion. A schematic diagram of the suggested binary geometry can be found in Tuthill *et al.* (1999a).

Mathematically, the outflow appears as an Archimedean spiral; in polar coordinates, $r = \alpha\theta$. The curvature of the spiral is controlled by the product of the wind speed and the period, which corresponds to the distance the dust travels during one period of the orbit. The period is determined from the apparent rotation manifest over multi-epoch data, and together with the curvature of the spiral, leads to a determination of the dust outflow velocity. Lastly, the Archimedean spiral shape must be projected onto the sky at some viewing angle. Circularity of the binary orbit was assumed (i.e. constant angular velocity) and led to an excellent simultaneous fit to the spiral morphology at all epochs, implying that the orbit is not highly eccentric. The current dataset is limited to only three epochs and does not justify the additional model complexity necessary to precisely estimate the orbital ec-

centricity.

4. RESULTS

For WR 98a, fits were done to the combined three-epoch dataset by sampling the K-band emission from the central bright core out to about 2% of the peak, resulting in the model curves of Figure 2. The period was found to be 565 ± 50 days, the viewing angle $35^\circ \pm 6^\circ$, and the angular velocity of the dust $99 \pm 23 \text{ mas yr}^{-1}$ (assuming a 565 day period); the uncertainties in these parameters were estimated as discussed below. Using a crude estimate of the outflow velocity, $\sim 900 \text{ km s}^{-1}$ based on near-IR linewidths (Williams *et al.* 1995), the angular velocity can be converted into a distance estimate of $\sim 1.9 \text{ kpc}$ (compare to $3 \pm 1 \text{ kpc}$ by Cohen *et al.* 1991). The period, outflow velocity, and estimated distance are similar to those obtained for the other known pinwheel nebula WR 104: 220 ± 30 days, $111 \pm 17 \text{ mas/yr}$, and $2.3 \pm 0.7 \text{ kpc}$ respectively (Tuthill *et al.* 1999a). However, the viewing angle of the WR 104 binary is significantly closer to the pole, $20^\circ \pm 5^\circ$.

The uncertainties in the model parameters were estimated by determining the span which yielded fits within 35% of the minimum χ^2 , and the suitability of this criterion was checked visually by inspecting fits with a variety of χ^2 . Because the morphology of the spiral curves is not greatly affected by the limited random noise in the maps, potential *systematic* errors (e.g., optical depth effects, limited spatial resolution, low-level MEM artifacts) are the primary causes of mis-estimation in model parameters.

Faint structures in the WR 98a maps ($\sim 2\%$ of peak) are present which do not appear to be part of the overall spiral morphology. In the June 1998 map, a spot or low-level extension appears east of the peak. Likewise in September 1998, low-level emission appears between the bright core and the outer spiral. Such additional emission was not present in WR 104 maps at any epoch, and requires an explanation beyond the simple outflow model developed in §3. While it is possible mapping artifacts are responsible for the apparent emission, the structures are present in all data for a given observing run and appear in CLEAN image reconstructions as well. We are left to conclude that the structures are probably real, but we cannot presently explain them.

5. DISCUSSION

The 1.55 yr (565 day) orbital period is in good agreement with the $\sim 1.4 \text{ yr}$ photometric period found by Williams *et al.* (1995). In Figure 5, K-band photometry from this paper has been plotted along with a pessimistic estimate of the uncertainty. In order to more precisely compare the possible periodicity in the IR flux with the estimated period of the binary, a sinusoid was fit to this data (see Figure 5) with best-fit parameters as follows: the mean magnitude is 4.52, the peak-to-trough amplitude is 0.65 mag, the date of maximum was 1992.59 and the period is 1.61 yrs (588 days).

Since this photometry only sparsely samples a 2.4 yr span, the 1.61 yr periodicity is difficult to firmly establish. However, this photometric period of 588 days is within errors of the binary orbital period of 565 ± 50 days derived in the last section. This unlikely coincidence suggests that

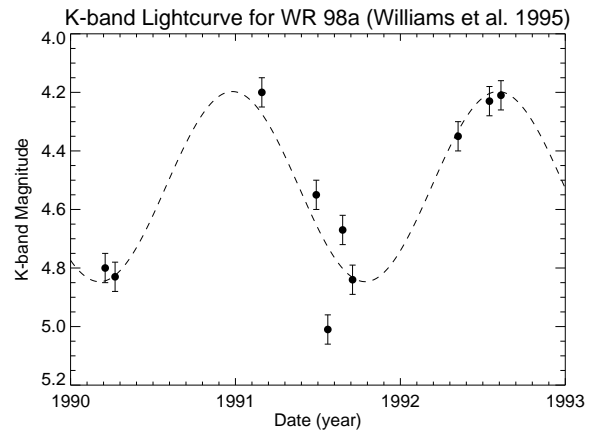


Fig 2.— K-band photometry of WR 98a, published in Williams *et al.* (1995), shows evidence of variation. The dashed line represents a best-fit sinusoid and the parameters are reported in the text (§5).

the variation in the IR flux is directly related to the binary itself, suggesting two possible scenarios. The 0.65 mag variation may be due to the relatively high (35°) viewing angle from the pole, varying optical depth and perspective could modulate the IR flux during the orbit. Alternatively, ellipticity in the binary orbit could cause the dust production rate to vary in time, causing the observed variation in IR (i.e. thermal) radiation. If the latter proves true, the eccentricity is likely to be small, based on the relatively small IR variation and the consistency of the three-epoch (circular) fit presented in §4. Recent unpublished photometry indicates that WR 98a was in the middle of its rising light curve in June 1998, near maximum light in September 1998, and fading in April 1999 (Williams 1999). Better sampling of the spiral emission morphology with coeval photometry through an orbital period is needed to determine the cause of IR variability and to precisely estimate the orbital eccentricity. In light of this, precision photometry of WR 104 should also be obtained in order to search for a similar flux modulation at the orbital period of its binary system (most recent period determination is 243.5 ± 3.0 days [Monnier 1999]).

6. IMPLICATIONS FOR BINARY EVOLUTION

Wolf-Rayet binary systems have been seen with periods $\gtrsim 10 \text{ yrs}$ and eccentric orbits which facilitate periodic dust production near periastron passage (WR 140 [Moffat *et al.* 1987; Williams *et al.* 1990], WR 19 [Veen *et al.* 1998], WR 137 [Marchenko, Moffat & Grosdidier 1999]). However, the periods of the *short-period* binaries reported around WR 104 and WR 98a are $\sim 1 \text{ yr}$ and the orbits appear nearly circular. Circularity of WR 104 is supported by both the lack of IR variability, indicating a constant dust production rate, and recent fits to four-epoch data under the assumption of circularity (Monnier [1999]). The level of ellipticity in the WR 98a orbit is not known, but fits to three epochs of data (presented here) and the small IR variability (as compared to long-period systems such as WR 140) do suggest the orbital eccentricity is small. Interestingly, the longest period WR + O system with a circular orbit previously known is of order 30 days (Tasoul 1990). Because of the unlikelihood of *a priori* circular orbits for non-interacting binaries, the possibility that the orbits of WR 104 and WR 98a were *circularized* must be

considered. For massive ($M \gtrsim 10 M_{\odot}$) stars, a ~ 1 yr binary period corresponds to a few AU in physical separation, while WR and O stars have radii of at most a few R_{\odot} . The efficiency of tidal circularization is quite sensitive to these parameters, and theory predicts no significant orbital circularization under these circumstances (Tassoul 1990; Verbunt & Phinney 1995). The observed circularity can be explained, however, if one of the stars was much larger in the past.

A WR star is characterized by the lack of a significant hydrogen envelope, lost during previous phases of evolution, especially the red supergiant phase (e.g., Vanbeveren *et al.* 1998). The diameter of a late-type red supergiant can easily exceed an AU (e.g., van Belle *et al.* 1999), and hence tidal forces and subsequent circularization effects must have been important at this evolutionary stage. The fact that the current component separation is about that of a red supergiant diameter (or smaller!) suggests that binary interaction, such as Roche lobe overflow, likely terminated the red supergiant phase, ejecting a large fraction of the hydrogen envelope, and leading to the onset of the WR-stage in the primary (Vanbeveren *et al.* [1998]). A large ejection of material could explain the high optical extinction to WR 104 (Cohen, Kuhl & Barlow 1975), despite a near pole-on viewing angle of the binary system. Similarly, heavy obscuration of a star only $\sim 3''$ away from WR 98a (Cohen *et al.* 1991; Williams *et al.* 1995) suggests the local presence of a large amount of unseen material.

If indeed persistent dust producing WR systems do imply the presence of a short-period binary, then we are left to explain the observed correlation of WR spectral type with the presence of dust; dust is preferentially observed around WC8-9 stars (Williams *et al.* 1987). These late-type WC stars are distinguished from the early-type through their wind ionization structure (Torres, Conti & Massey 1986), which is not, by itself, a clear signature of previous binary interactions. One explanation is that the enhanced mass-loss associated with the formation of circular, ~ 1 yr binaries may lead to WR stars with late-WC properties, i.e. lower terminal velocities and less-excited

wind ionization structure. The high mass-loss rates associated with close-binary evolution may well tend to produce WR stars with stellar parameters (e.g., low core mass) most hospitable to dust formation. On the other hand, efficient dust formation may require both of these conditions to be simultaneously and independently satisfied: a short-period binary system for gas-compression and a late-type WR star with cool temperatures and appropriate chemistry. If this is the case, one would expect to find a number of WR(early)+OB binaries with periods of ~ 1 year, a class as-yet-unidentified (e.g., see Table 3 in Vanbeveren *et al.* [1998]).

7. CONCLUSIONS

We report new multi-epoch images of the pinwheel nebula around WR 98a at $2.2\mu\text{m}$. By assuming the dust forms via colliding winds, orbital parameters of the underlying binary system have been estimated. The recent discoveries of pinwheel nebulae around dusty WR stars have made possible a new approach for identifying and characterizing embedded WR+O binary systems with ~ 1 yr periods, systems difficult to identify by any other means. The inferred component separations and high degree of orbital circularity suggest these systems evolved from red supergiant + OB binaries, a phase which was terminated by Roche-lobe overflow and the production of the obscured Wolf-Rayet systems we see today.

We acknowledge enlightening discussions with L. Bildsten regarding circularization time scales and binary stellar evolution. We would like to thank D. Sivia for the maximum-entropy mapping program “VLBMEM,” and C.D. Matzner, L.J. Greenhill, K. van der Hucht, and P. Williams for their helpful comments. This research has made use of the SIMBAD database and NASA’s ADS Abstract Service. The data presented herein were obtained at the Keck Observatory, which is operated as a scientific partnership among Caltech, the University of California and NASA. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. This work was supported by the NSF (AST-9315485 & AST-9731625) and the ONR (ONR N00014-97-1-0743-05).

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